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Experimental study of discharging PCM ceiling panels through nocturnal radiative cooling

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ABSTRACT

PhotoVoltaic/Thermal (PV/T) panels were used for cooling water through the principle of nocturnal radiative cooling. This water was utilised for discharging Phase Change Material (PCM) which was embedded in ceiling panels in a climate chamber. Three different sets of flow rates were examined for the solar and the PCM loops, for five days each. The highest examined water flow rate (210 l/h) in the PCM loop provided the best thermal environment in the climate chamber, namely 92% of the occupancy time was within the range of Category III of Standard EN 15251. Although the lowest examined water flow rate (96 l/h) in the solar loop provided the highest average cooling power, due to the significant variations in the weather conditions during the three experimental cases, made it impossible to determine to which extent the difference in the cooling power is due to the different water flow rate. The percentage of electrical energy use that could be covered from the PV/Ts on site was 71.5% for Case 1, 68.3% for Case 2 and 86.8% for Case 3. In any case, the PV/T panels proved to be an efficient solution for the production of electrical energy, heated and chilled water.

KEYWORDS

Ceiling cooling panels, Phase change material, nocturnal radiative cooling, Photovoltaic/thermal panels, High temperature cooling

INTRODUCTION

Following the outcome of the recent United Nations Conference on Climate Change 2015 (UNFCCC 2015) and the recently adopted policies from the European Union (EP 2009; EP 2010) vast changes have to be implemented in the buildings sector, such as installing photovoltaic panels on existing building or increasing the efficiency of the heating, ventilation and air conditioning (HVAC) equipment. According to UNEP (2009) the majority of the buildings that will exist by the year 2050 in the developed countries have already been built. Therefore, the interest should be focused on renovating existing buildings.

A solution that could contribute in energy retrofitting existing buildings and at the same time improving the interior thermal conditions could be the installation of ceiling panels with phase change material (PCM). PCMs are either organic or inorganic substances that store large amounts of energy when they melt and release it when they solidify. During the phase change the temperature of the PCM remains constant resulting in a lower surface temperature compared to a conventional material that would absorb the same amount of heat (Kuznik et al. 2011). The most important advantages of installing ceiling panels with PCM are the reduction of the peak cooling load, the shift of fraction of the cooling demand to night-time, the reduced temperature span and the reduction of the size of the HVAC system (Koschenz & Lehmann 2004; Cabeza et al. 2007; Pavlov 2014).

A possible method to discharge the PCM passively consists in exploiting solar panels during the night through the process of radiative cooling. Night sky can be used as a natural heat sink, since its effective temperature, depending on the weather conditions, can be significantly lower than the ambient temperature. Therefore, water circulated during night-time in solar panels can be cooled down passively and utilised for discharging the PCM panels. The benefits of exploiting night-time radiative cooling are the higher utilization factor of solar panels, the possible coupling with thermal storage systems(e.g. PCM), and the fact that cold water production and cooling demand are in phase. Indeed, clear sky occurs more often during summer time when the cooling demand is higher (Meir et al. 2002; Eicker & Dalibard 2011; Hosseinzadeh & Taherian 2012; Péan et al. 2015).
The purpose of the present experiment was to realize the coupling of solar panels with PCM ceiling panels and examine different water flow rates circulating in the two loops to identify the optimum combination.

METHODS

The experiment took place at the facilities of the International Centre for Indoor Environment and Energy at the Technical University of Denmark, during June 2015. For simulating a two persons' office, a climatic chamber that is inside a greater building was used, therefore this chamber was not affected from changes in the ambient weather conditions. The floor area of the chamber was 22.7 m² while the height of the chamber was 3 m. The floor, the roof and the four walls of the chamber were made of two aluminium plates and 100 mm of mineral wool between them.
At 2.5 m above the floor, 24 ceiling panels containing the PCM were installed, forming a 0.5 m plenum above the office room. The surface of each panel was 0.78 m² and the thickness was 25 mm. Each panel contained 6 kg of PCM, corresponding to 26% of the total weight of each panel. The fusion temperature of the PCM used was 23°C. Alu-PEX pipes were installed inside the panels in order to discharge the PCM by recirculating cold water.
Heat dummies were used for simulating the two occupants and the office equipment, and they were activated from 09:00 until 17:00 which are considered typical office hours. The total internal heat gains from the occupants, the equipment, the desk lamps and the ceiling lamps were 540W (23.8 W/m²). Since the chamber was not exposed directly to solar heat gains, an electrical heating panel was used to simulate the solar heat gains of a window facing south. The setup of the climatic chamber is shown in Figure 1; the electrical heating panel is located in the background.

Figure 1: The interior of the climatic chamber

Air was supplied to the office from the plenum above the suspended ceiling. The air flow rate was 30 l/s (1.9 ACH), sized according to Standard EN 15251 (DS/EN 2007) for removing

latent heat gains and pollutants. The air supply temperature was varying between 18°C and 20°C.
On the roof of the building where the chamber was installed, three PV/T panels were installed in series. The panels were facing south with an angle of 45° and the surface of each panel was 1.3 m^2. The PV/T panels were connected with two storage tanks through a plate surface heat exchanger, as it is shown in Figure 2. In the first tank hot water was stored (HWT), while in the other one cold water (CWT) was stored. The direction of the water after the heat exchanger was determined automatically based on the two following equations:

- If $T_{PV/T} - T_{HWT} > 1\ K$ then the water was directed towards the HWT
- If $T_{CWT} - T_{(PV/T)} > 1\ K$ then the water was directed towards the CWT

where $T_{(PV/T)}$ is the temperature exiting the PV/T panels, T_{HWT} is the temperature in the middle of the HWT and T_{CWT} is the temperature in the middle of the CWT. If neither of the two conditions was met, then the pump located between the plate surface heat exchanger and the tanks was deactivated. The locations of these three sensors are shown in Figure 2.

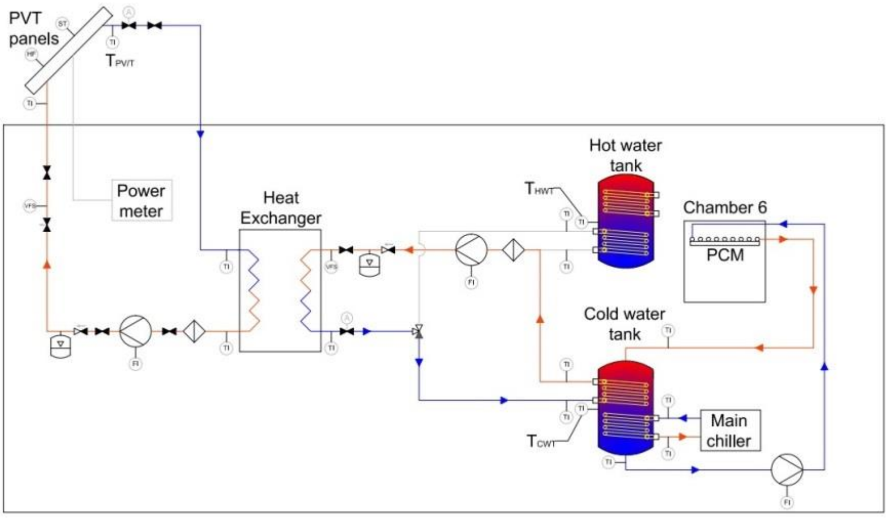

Figure 2: Schematic drawing of the hydraulic system

As it is shown in Figure 2, the CWT had two internal spiral heat exchangers. The upper one was connected with the plate surface heat exchanger, while the lower one was connected with the main chiller of the facilities. The main chiller was used as a backup system for providing cold water in case the production from the night-time radiative cooling was not sufficient to reduce the temperature in the CWT. If it was required, the chiller would operate during the period 05:00 – 09:00. The water supply temperature of the main chiller was 7°C. The water stored in the CWT was circulated to the ceiling panels to discharge the PCM, provided that all three following conditions were met:

- The average lower surface temperature of the ceiling panels was above 21°C
- The operative temperature of the office room was above 21°C
- The temperature of the water in the middle of the CWT was below 20°C

During the occupancy period (09:00 – 17:00) water from the CWT would be circulated in the ceiling panels in case the operative temperature in the office was exceeding 25.5°C and the temperature in the middle of the CWT was below 20°C.

The three different cases that were examined are presented in Table 1. The duration for each case was five consecutive days. During the whole experimental period, the electrical power of the PV/T panels was also monitored.

Table 1. Cases examined

Case number	Solar loop water flow rate, l/h	PCM loop water flow rate, l/h
1	216	150
2	166	180
3	94	210

RESULTS

In Figure 3 the operative temperature of the three examined cases is presented. The horizontal pairs of dashed lines are the lower and upper limits of the three categories of Standard 15251 (DS/EN 2007). The temperature ranges for each category are 23.5 – 25.5°C for Category I, 23 – 26°C Category II and 22 – 27°C for Category III. The gray shaded areas are the occupancy period, namely from 09:00 to 17:00, each day. The sudden drop that is observed after 05:00 during the nights was by the activation of the chiller, causing the temperature in the CWT to drop drastically.

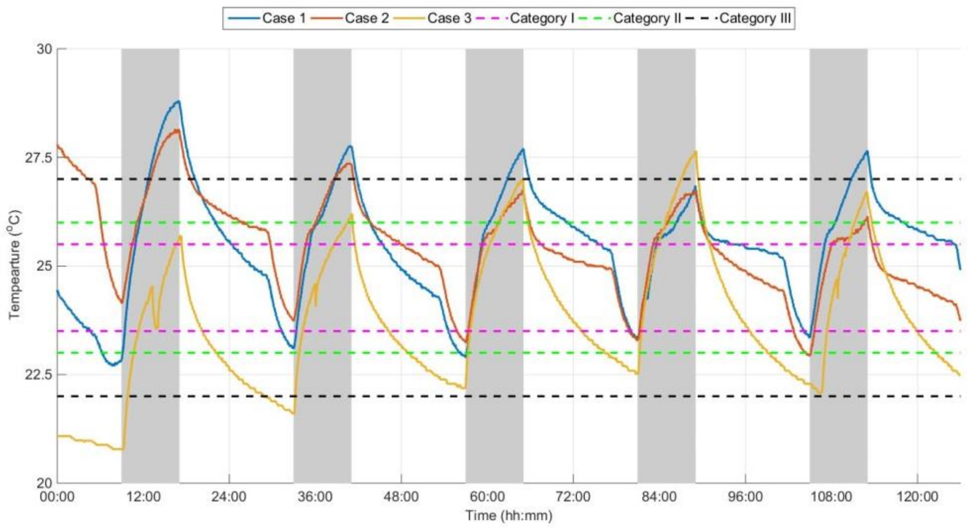

Figure 3. Operative temperature over time

The percentage of occupancy time when the temperature was within the range of each category of Standard 15251 (DS/EN 2007) is presented in Table 2.

Table 2. Percentage of occupancy time in each category of Standard 15251 (DS/EN 2007)

Case number	Percentage of occupancy time in Category I, %	Percentage of occupancy time in Category II, %	Percentage of occupancy time in Category III, %
1	23	45	72
2	24	53	84
3	45	63	92

The average power output of the PV/T panels in terms of electrical, hot water and cold water production are presented in Table 3.

Table 3. Average power outputs of the PV/T panels

Case number	Average electrical power, W/m^2	Average heating power, W/m^2	Average cooling power, W/m^2
1	53.8	41.5	61.9
2	49.3	33.9	65.8
3	51.0	35.0	70.8

A comparison between the electrical energy produced by the PV/Ts and the electrical energy use for each experiment is presented is presented in Figure 4. The electrical energy production was 18.8 kWh, 16.8 kWh and 16.9 kWh for Case 1, 2 and 3, respectively. The electrical energy use is separated into electrical energy use for the office equipment, the pumps, the ventilation and the chiller. The office equipment consisted of two laptops with one screen each, four ceiling lamps and two office lamps and the total energy use was 9.1 kWh for each case. The pumps tab shows the energy usage of the three pumps shown in Figure 2, and it varied between 1.6 kWh in Case 3 and 2.7 kWh in Case 1. The ventilation tab includes the energy use of the fan and the cooling coil and it was 1.2 kWh for all three cases. Because the specific fan power (SFP) of the fan was unknown, an SFP of 1000 $W/(m^3/s)$ was assumed based on the required flow rate. The electrical energy use of the chiller was 7.5 kWh for Case 3, 12.1 for Case 2 and 13.3 for Case 1. In order to calculate the energy use of the cooling coil and the chiller, it was assumed that the HVAC was connected to an air to water heat pump. The specifications of a heat pump available on the market were used, based on which a seasonal COP of 4.5 was calculated. The total energy was 26.3 kWh, 24.6 and 19.5 kWh for Cases 1, 2 and 3 respectively. The percentage of electrical energy use that could be covered from the PV/Ts on site was 71.5% for Case 1, 68.3% for Case 2 and 86.8% for Case 3.

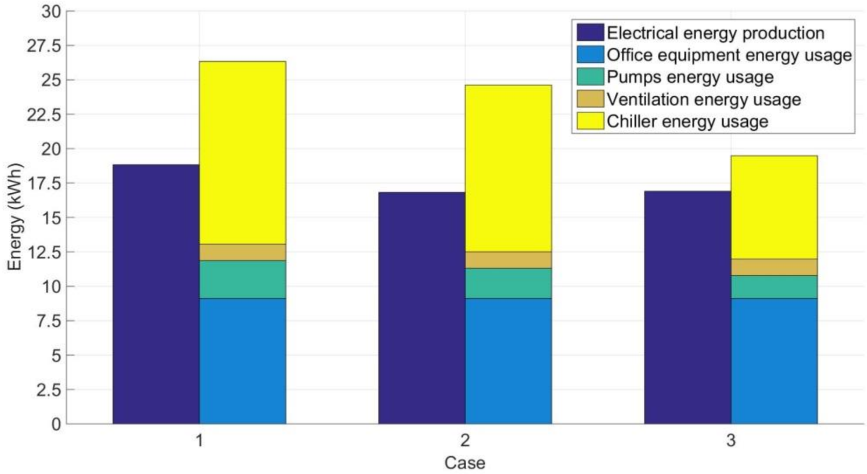

Figure 4. Electrical energy production vs energy use comparison

DISCUSSIONS

From the results presented in Figure 3 and Table 2 it can be seen that the case where the best thermal environment was provided in the chamber was Case 3. The air temperature in the building where the climate chamber was located is presented in Figure 5. The average air temperature measured outside the chamber for each case was 25.2°C for Case 1, 24.5°C for Case 2 and 25.4°C for Case 3. Since the building's average air temperature difference among the three cases is not significant and the chamber was not exposed to direct solar radiation, it can be concluded that the differences observed in the thermal performance of the chamber were attributed to the change of the flow rate of the pump circulating water to the PCM panels.

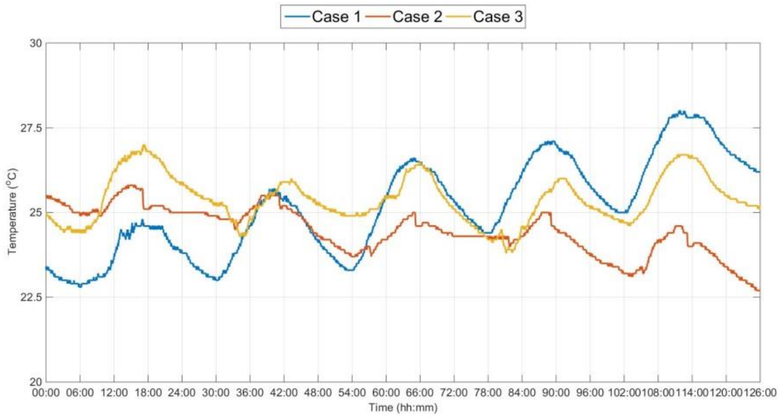

Figure 5. Air temperature outside the chamber

The higher average electrical power of Case 1 reported in Table 3 and consequently the higher electrical energy production shown in Figure 4 are attributed to the higher solar radiation on the panels during that Case, as it is shown in Table 4. These weather data were recorded by a weather station installed next to the PV/T panels.

Table 4. Weather conditions during the experiment

Case Number	Minimum ambient air temperature, °C	Maximum ambient air temperature, °C	Average ambient air temperature, °C	Solar energy on the panels, kWh/m^2	Max. wind speed, m/s	Aver. wind speed, m/s
1	12.0	27.8	18.9	2220	4.5	1.5
2	12.3	21.4	17.4	1795	7.2	1.9
3	11.1	24.7	18.1	1656	5.4	1.2

The variation of the solar radiation and the ambient air temperature between the three cases shown in Table 4 and Figure 6, affected the heating power output of the PV/Ts and therefore it cannot be concluded which flow rate in the solar loop is the most effective for water heating.

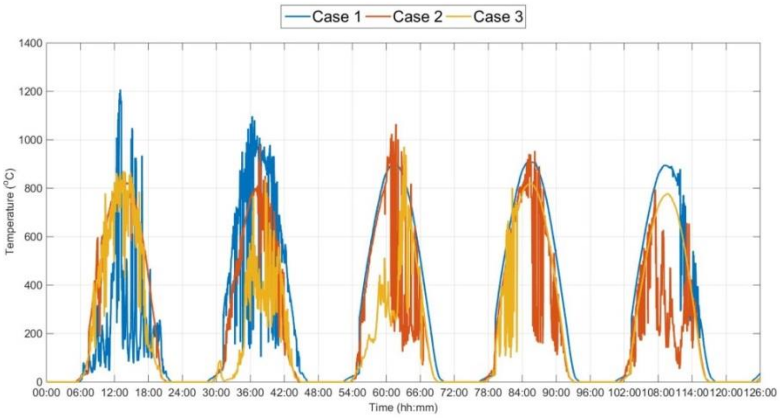

Figure 6. Solar radiation over time

The cooling power of the PV/Ts is determined by the convection on the surface of the panels and the radiation towards the sky. The installed weather station did not have the possibility of recording the percentage of cloud cover, therefore the only indication of the effect of the weather conditions on the cooling power is through the ambient air temperature and the wind speed, both affecting the convection on the panels' surface. As can be seen from Table 4 and Figure 7 considerable variations were observed in both weather parameters among the three experimental cases. Therefore, as before it cannot be concluded which flow rate in the solar loop was the most beneficial for cooling the water.

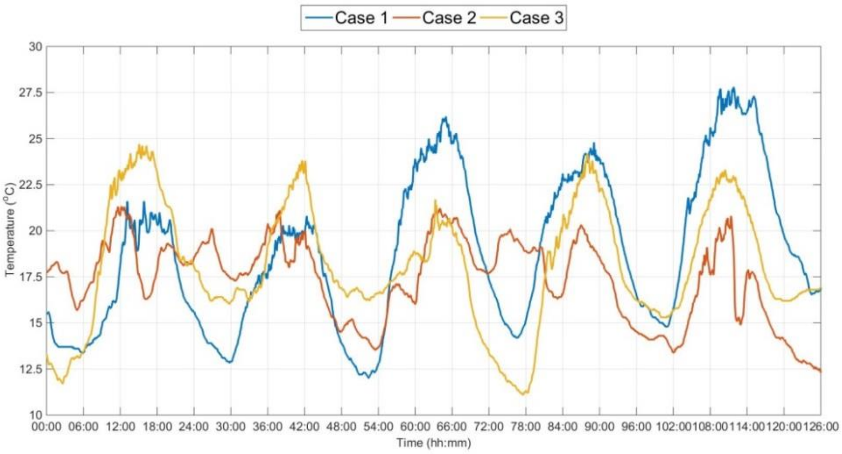

Figure 7. Ambient air temperature over time

The PV/T panels did not provide all the electrical energy required for the chamber, but it should be taken into consideration that the electrical energy demand would be higher if regular photovoltaic panels were used due to the demand for heating and cooling covered by the PV/T panels. As mentioned before, it was assumed that an air to water heat pump was used. If a water to water heat pump or a ground source heat exchanger were used instead, a higher COP would have been estimated and therefore the energy use of the chiller and the cooling coil would be lower. The difference in the electrical energy production among the three cases was not significant, but in Case 3 the chiller operated for considerably lower amount of time, resulting in lower energy use compared to the previous two cases. That resulted in the higher percentage of electrical energy use covered by the PV/Ts for the 3rd case.

CONCLUSIONS

1. It was concluded that out of the three examined flow rates in the PCM loop, the highest one provided the best thermal environment in the chamber. 2. The variations in the weather conditions between the three cases cannot lead to a safe conclusion whether the measured differences in the heating and cooling power of the PV/Ts can be attributed to the different flow rate in the solar loop or the weather conditions. 3. PV/T panels proved to be an efficient solution for the production of electrical energy and heating and cooling water for domestic hot water and space cooling respectively.

ACKNOWLEDGEMENT

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